

# *Hawley's Condensed Chemical Dictionary*

*ELEVENTH EDITION*

*Revised by*

N. Irving Sax  
and  
Richard J. Lewis, Sr.



VAN NOSTRAND REINHOLD COMPANY

New York

**HANDBOOK**

By Philip

Here's the

for A.I.L.

up proceed

essory e

asic thed

57/90X

**PUMP HAN**

Edited by

1.102 pp.

Prepared

ence cover

maintenan

organizin

handbook

aids. inclu

333/017

**HANDBOOK**

Edited by

A classic o

draulic str

branches o

examples o

155/380

**HANDBOOK**

Edited by

A systema

ciency, and

shows you

More than

do everyth

he field.

287/643

**ELECTRONIC**

Edited by L

This famou

thoroughly

hor. teache

han 90 of it

nce for any

covered stre

he how muc

131/494

**CHEMICAL EN**

Edited by R

illus., charts

Provides eve

olve today

question ab

The 25 sect

updated, rev

em-solving

194/789

Copyright © 1987 by Van Nostrand Reinhold Company Inc.

Library of Congress Catalog Card Number: 86-23333

ISBN: 0-442-28097-1

All rights reserved. Certain portions of this work copyright © 1930, 1920, 1919 by The Chemical Catalog Co., Inc. and 1981, 1977, 1971, 1966, 1956, 1950 by Van Nostrand Reinhold Company Inc. No part of this work covered by the copyright hereon may be reproduced or used in any form or by any means—graphic, electronic, or mechanical, including photocopying, recording, taping, or information storage and retrieval systems—without permission of the publisher.

Printed in the United States of America

Van Nostrand Reinhold Company Inc.

115 Fifth Avenue

New York, New York 10003

Van Nostrand Reinhold Company Limited

Molly Millars Lane

Wokingham, Berkshire RG11 2PY, England

Van Nostrand Reinhold

480 Latrobe Street

Melbourne, Victoria 3000, Australia

Macmillan of Canada

Division of Canada Publishing Corporation

164 Commander Boulevard

Agincourt, Ontario M1S 3C7, Canada

15 14 13 12 11 10 9 8 7 6 5 4 3

**Library of Congress Cataloging-in-Publication Data**

Condensed chemical dictionary.

Hawley's condensed chemical dictionary.

Rev. ed. of: The Condensed chemical dictionary.

10th ed./rev. by Gessner G. Hawley, 1981.

I. Chemistry—Dictionaries. I. Hawley, Gessner

Goodrich, 1905— II. Sax, N. Irving (Newton Irving)

III. Lewis, Richard J., Sr. IV. Title.

QD5.C5 1987 540'.3'21 86-23333

ISBN 0-442-28097-1

**solvation.** In the parlance of colloid chemistry, the adsorption of a monolayer or film of water or other solvent on individual dispersed particles of a solution or dispersion. The term "solvated hulls" has been used to describe such particles. It is also applied to the action of plasticizers on resin dispersions in plastisols. See also hydration (2).

**Solvay process.** (ammonia soda process).

Manufacture of sodium carbonate (soda ash,  $\text{Na}_2\text{CO}_3$ ) from salt, ammonia, carbon dioxide, and limestone by an ingenious sequence of reactions involving recovery and reuse of practically all the ammonia and part of the carbon dioxide. Limestone is heated to produce lime and carbon dioxide. The latter is dissolved in water containing the ammonia and salt, with resultant precipitation of sodium bicarbonate. This is separated by filtration, dried, and heated to form normal sodium carbonate. The liquor from the bicarbonate filtration is heated and treated with lime to regenerate the ammonia. Calcium chloride is a major byproduct. *Note:* Because this process requires much energy and pollutes streams and rivers with chloride effluent many plants using it have closed, production being obtained from the natural deposits in the Western US.

**"Solvenol."**<sup>TM</sup> 266 TM for a group of monocyclic terpene hydrocarbons with minor amounts of terpene alcohols and ketones.

Use: General solvent, rubber reclaiming.

**solvent.** A substance capable of dissolving another substance (solute) to form a uniformly dispersed mixture (solution) at the molecular or ionic size level. Solvents are either polar (high dielectric constant) or non-polar (low dielectric constant). Water, the most common of all solvents, is strongly polar (dielectric constant 81), but hydrocarbon solvents are non-polar. Aromatic hydrocarbons have higher solvent power than aliphatics (alcohols). Other organic solvent groups are esters, ethers, ketones, amines, and nitrated and chlorinated hydrocarbons.

The chief uses of organic solvents are in the coatings field (paints, varnishes and lacquers), industrial cleaners, printing inks, extractive processes, and pharmaceuticals. Since many solvents are flammable and toxic to varying degrees, they contribute to air pollution and fire hazards. For this reason their use in coatings and cleaners has declined in recent years.

See individual compounds.

**solvent, aprotic.** A solvent that cannot act as a proton acceptor or donor i.e., as an acid or base.

**solvent drying.** Removal of water from metal surfaces by means of a solvent that displaces it

preferentially, as on precision equipment, electronic components, etc. Examples of solvents used are acetone, 1,1,2-trichloro-1,2,2-trifluoroethane, 1,1,1-trichloroethane.

**solvent dye.** See dye, solvent.

**\*solvent extraction.** A separation operation which may involve three types of mixture: (a) a mixture composed of two or more solids, such as a metallic ore; (b) a mixture composed of a solid and a liquid; (c) a mixture of two or more liquids. One or more components of such mixture are removed (extracted) by exposing the mixture to the action of a solvent in which the component to be removed is soluble. If the mixture consists of two or more solids, extraction is performed by percolation of an appropriate solvent through it. This procedure is also called leaching, especially if the solvent is water; coffee-making is an example. Synthetic fuels can be made from coal by extraction with a coal-derived solvent followed by hydrogenation.

In liquid-liquid extraction one or more components are removed from a liquid mixture by intimate contact with a second liquid which is itself nearly insoluble in the first liquid and dissolves the impurities and not the substance that is to be purified. In other cases the second liquid may dissolve, i.e., extract from the first liquid, the component that is to be purified, and leave associated impurities in the first liquid. Liquid-liquid extraction may be carried out by simply mixing the two liquids with agitation and then allowing them to separate by standing. It is often economical to use counter-current extraction, in which the two immiscible liquids are caused to flow past or through one another in opposite directions. Thus fine droplets of heavier liquid can be caused to pass downward through the lighter liquid in a vertical tube or tower.

The solvents used vary with the nature of the products involved. Widely used are water, hexane, acetone, isopropyl alcohol, furfural, xylene, liquid sulfur dioxide, and tributyl phosphate. Solvent extraction is an important method of both producing and purifying such products as lubricating and vegetable oils, pharmaceuticals and nonferrous metals.

**solvent, latent.** (co-solvent). An organic liquid that will dissolve nitrocellulose in combination with an active solvent. Latent solvents are usually alcohols and are used widely in nitrocellulose lacquers in a ratio of 1 part alcohol to 2 parts active solvent.

**solvent naphtha.** See naphtha (2b).

**Solvent Red 73.** See 4',5'-diiodofluorescein.

POLYCRYSTALLINE CONDUCTING POLYMERS AND PRECURSORS  
THEREOF  
HAVING ADJUSTABLE MORPHOLOGY AND PROPERTIES

Cross Reference to Related Application

U.S. Patent Application Serial No. 08/620619 entitled, "PLASTICIZED, ANTIPLASTICIZED CRYSTALLINE CONDUCTING POLYMERS AND PRECURSORS THEREOF" and U.S. Patent Application Serial No. 08/621631 entitled, "METHODS OF FABRICATING PLASTICIZED, ANTIPLASTICIZED AND CRYSTALLINE CONDUCTING POLYMERS AND PRECURSORS THEREOF", the teachings of which are incorporated herein by reference.

This application claims priority from Provisional Application Serial No. 60/007,688 filed November 29, 1995.

FIELD OF THE INVENTION

The present invention is directed to polycrystalline electrically conductive polymer precursors and polycrystalline conducting polymers having adjustable morphology and properties.

BACKGROUND

Electrically conductive organic polymers emerged in the 1970's as a new class of electronic materials. These materials have the potential of combining the electronic and magnetic properties of metals with the light weight, processing advantages, and physical and mechanical properties characteristic of conventional organic polymers. Examples of electrically conducting polymers are polyparaphenylene vinylenes, polyparaphenylenes, polyanilines, polythiophenes, polyazines, polyfurans, polythianaphthenes polypyrroles, polyselenophenes, poly-p-phenylene sulfides, polyacetylenes formed from soluble precursors, combinations thereof and blends thereof with other polymers and copolymers of the monomers thereof.

These polymers are conjugated systems which are made electrically conducting by doping. The doping reaction can involve an oxidation, a reduction, a protonation, an alkylation, etc. The non-doped or non-conducting form of the polymer is referred to herein as the precursor to the electrically conducting polymer. The doped or conducting form of the polymer is referred to herein as the conducting polymer.

Conducting polymers have potential for a large number of applications in such areas such as electrostatic charge/discharge (ESC/ESD) protection, electromagnetic interference (EMI) shielding, resists, electroplating, corrosion protection of metals, and ultimately metal replacements, i.e. wiring, plastic microcircuits, conducting pastes for various interconnection technologies (solder alternative), etc. Many of the above applications especially those requiring high current capacity have not yet been realized because the conductivity of the processible conducting polymers is not yet adequate for such applications.

To date, polyacetylene exhibits the highest conductivity of all the conducting polymers. The reason for this is that polyacetylene can be synthesized in a highly crystalline form (crystallinity as high as 90% has been achieved) (as reported in *Macromolecules*, 25, 4106, 1992). This highly crystalline polyacetylene has a conductivity on the order of  $10^5$  S/cm. Although this conductivity is comparable to that of copper, polyacetylene is not technologically applicable because it is a non-soluble, non-processible, and environmentally unstable polymer.

The polyaniline class of conducting polymers has been shown to be probably the most suited of such materials for commercial applications. Great strides have been made in making the material quite processable. It is environmentally stable and allows chemical flexibility which in turn allows tailoring of its properties. Polyaniline coatings have been developed and commercialized for numerous applications. Devices and batteries have also been constructed with this material. However, the conductivity of this class of polymers is generally on the low end of the metallic regime. The conductivity is on the order of  $10^0$  S/cm. Some of the other soluble conducting polymers such as the polythiophenes, poly-para-phenylenevinylenes exhibit conductivity on the order of  $10^2$  S/cm. It is therefore desirable to increase the conductivity of the soluble/processible conducting polymers, in particular the polyaniline materials.

The conductivity ( $\sigma$ ) is dependent on the number of carriers ( $n$ ) set by the doping level, the charge on the carriers ( $q$ ) and on the interchain and intrachain mobility ( $\mu$ ) of the carriers.

$$\sigma = n q \mu$$

Generally,  $n$  (the number of carriers) in these systems is maximized and thus, the conductivity is dependent on the mobility of the carriers. To achieve higher conductivity, the mobility in these systems needs to be increased. The mobility, in turn, depends on the morphology of the polymer. The intrachain mobility depends on the degree of conjugation along the chain, presence of defects, and on the chain conformation. The interchain mobility depends on the interchain interactions, the interchain distance, the degree of crystallinity, etc. Increasing the crystallinity results in increased conductivity as exemplified by polyacetylene. To date, it has proven quite difficult to attain polyaniline in a highly crystalline state. Some crystallinity has been achieved by stretch orientation or mechanical deformation (A.G. MacDiarmid et al in Synth. Met. 55-57, 753). In these stretch-oriented systems, conductivity enhancements have been observed. The conductivity enhancement was generally that measured parallel to the stretch direction. Therefore, the conductivity in these systems is anisotropic. It is desirable to achieve a method of controlling and tuning the morphology of polyaniline. It is desirable to achieve a method of controlling and tuning the degree of crystallinity and the degree of amorphous regions in polyaniline, which in turn provides a method of tuning the physical, mechanical, and electrical properties of polyaniline. It is further desirable to achieve highly crystalline and crystalline polyaniline and to achieve this in a simple and useful manner in order to increase the mobility of the carriers and, therefore, the conductivity of the polymer. It is also further desirable to achieve isotropic conductivity, that is conductivity not dependent on direction as with stretch-oriented polyanilines.

#### OBJECTS

It is an object of the present invention to provide a polycrystalline material containing crystallites of an electrically conducting polymer precursor and/or electrically conducting polymer having an adjustable morphology.

It is an object of the present invention to provide a polycrystalline material of an electrically conductive polymer precursor and/or electrically conducting polymer in which the degree of amorphous and crystalline regions is adjustable.

It is an object of the present invention to provide a polycrystalline material of an electrically conducting polymer precursor and/or electrically conducting polymer having adjustable physical, mechanical, and electrical properties.

It is an object of the present invention to provide a crystalline electrically conducting polymer precursor and crystalline conducting polymers.

It is an object of the present invention to provide a highly crystalline electrically conducting polymer precursor and highly crystalline conducting polymers.

It is an object of the present invention to provide a polycrystalline material of an electrically conducting polymer precursor and/or crystalline conducting polymers to provide a highly crystalline material.

It is another object of the present invention to provide an electrically-conducting polycrystalline material that exhibits enhanced carrier mobility.

It is another object of the present invention to provide an electrically conducting polycrystalline material which exhibits enhanced conductivity.

It is another object of the present invention to provide an electrically conducting polycrystalline material which exhibits enhanced isotropic conductivity.

It is another object of the present invention to provide a plasticization effect in a polycrystalline electrically conducting polymer precursors and/or electrically conducting polymers.

It is another object of the present invention to provide a polycrystalline material having an antiplasticization effect in electrically conducting polymer precursors and electrically conducting polymers.

It is another object of the present invention to provide a polycrystalline material of a precursor or electrically conducting polymer containing an additive providing mobility.

It is another object of the present invention to provide a polycrystalline material of a precursor or electrically conductive polymer containing an additive to induce an enhanced degree of crystallinity.

It is another object of the present invention to provide a non-stretch oriented polycrystalline film of a precursor or of an electrically conductive polymer which has an enhanced degree of crystallinity.

It is an object of the present invention to provide a polycrystalline material of an electrically conducting polymer precursor and/or electrically conducting polymer having an increased glass transition temperature.

It is an object of the present invention to provide an electrically conducting polymer precursor and electrically conducting polymer having a decreased glass transition temperature.

It is an object of the present invention to provide a polycrystalline material of an electrically conducting polymer precursor and electrically conducting polymer having enhanced mechanical properties.

It is an object of the present invention to provide a polycrystalline material of an electrically conducting polymer precursor and electrically conducting polymer having decreased mechanical properties.

#### SUMMARY OF THE INVENTION

A broad aspect of the present invention is a polycrystalline material comprising crystallites of a precursor to an electrically conductive polymer and/or an electrically conductive polymer. The interstitial regions between the crystallites contain amorphous material.

In a more particular aspect of the present invention, the amorphous regions of the material contain the additive.

## BRIEF DESCRIPTION OF THE DRAWINGS

Further objects, features, and advantages of the present invention will become apparent from a consideration of the following detailed description of the invention when read in conjunction with the drawings FIG's. in which:

Fig. 1 is a general formula for polyaniline in the non-doped or precursor form.

Fig. 2 is a general formula for a doped conducting polyaniline.

Fig. 3 is a general formula for the polysemiquinone radical cation form of doped conducting polyaniline.

Fig. 4 is a Gel Permeation Chromatograph (GPC) of polyaniline base in NMP (1 %). GPC shows a trimodal distribution- A very high molecular weight fraction (approx. 12%) and a major peak having lower molecular weight.

Curve 5(a) is a Wide Angle X-Ray Scattering (WAXS) spectrum for a polyaniline base film processed from NMP. The polymer film is essentially amorphous. Curve 5(b) is a Wide Angle X-Ray Scattering spectrum for a polyaniline base film that has been stretch-oriented ( $l/l_0 = 3.7$ ). This film was derived from a gel. Curve 5(c) is a Wide Angle X-Ray Scattering spectrum for a polyaniline base film containing 10% of poly-co-dimethyl propylamine siloxane. This film is highly crystalline.

Fig. 6 is a Schematic diagram of a polycrystalline material as taught in present invention having crystalline regions (outlined in dotted rectangles) with interstitial amorphous regions

Fig.7 is a Dynamic Mechanical Thermal Analysis (DMTA) plot for polyaniline base film cast from NMP. (First Thermal Scan; under Nitrogen).

Fig. 8 is a DMTA plot which represents the second thermal scan for a polyaniline base film cast from NMP; This same film was previously scanned as shown in Fig.7. Film Contains no residual solvent.

Fig. 9 is a DMTA plot for polyaniline base film cast from NMP and containing 5% poly-co-dimethyl aminopropyl siloxane (5% N content). First Thermal Scan.

Fig. 10 is a DMTA plot for polyaniline base film cast from NMP and containing 5% poly-co-dimethyl aminopropyl siloxane (5% N content). Second Thermal Scan (this same film was previously scanned as shown in Fig. 9) Film Contains no residual solvent.

Fig. 11 is a GPC for a polyaniline base solution in NMP containing 5% poly-co-dimethyl aminopropyl siloxane by weight to polyaniline. The polyaniline was .1% in NMP.

#### DETAILED DESCRIPTION

The present invention is directed toward electrically conducting polymer precursors and conducting polymers having adjustable morphology and in turn adjustable physical,

mechanical, and electrical properties. The present invention is also directed toward controlling and enhancing the 3-dimensional order or crystallinity of conducting polymer precursors and of conducting polymers. In addition, the present invention is directed towards enhancing the electrical conductivity of conducting polymers. This is done by forming an admixture of an electrically conducting polymer precursor or an electrically conducting polymer with an additive whereby the additive provides local mobility to the molecules so as to allow the conducting polymer precursor or conducting polymer chains to associate with one another and achieve a highly crystalline state. An example of such an additive is a plasticizer. A plasticizer is a substance which when added to a polymer, solvates the polymer and increases its flexibility, deformability, generally decreases the glass transition temperature  $T_g$ , and generally reduces the tensile modulus. In certain cases, the addition of a plasticizer may induce antiplasticization, that is an increase in the modulus or stiffness of the polymer, an increase in  $T_g$ . Herein the additives can provide a plasticization effect, an antiplasticization effect or both effects.

Examples of polymers which can be used to practice the present invention are of substituted and unsubstituted homopolymers and copolymers of aniline, thiophene, pyrrole, p-phenylene sulfide, azines, selenophenes, furans, thianaphthenes, phenylene vinylene, etc. and the substituted and unsubstituted polymers, polyparaphenylenes, polyparaphenylenevinylenes, polyanilines, polyazines, polythiophenes, poly-p-phenylene sulfides, polyfurans, polypyrroles, polythianaphthenes, polyselenophenes, polyacetylenes formed from soluble precursors and combinations thereof and copolymers of monomers thereof. The general formula for these polymers can be found in U.S. Patent 5,198,153 to Angelopoulos et al. While the present invention will be described with reference to a preferred embodiment, it is not limited thereto. It will be readily apparent to a person of skill in the art how to extend the teaching herein to other

embodiments. One type of polymer which is useful to practice the present invention is a substituted or unsubstituted polyaniline or copolymers of polyaniline having general formula shown in Fig. 1 wherein each R can be H or any organic or inorganic radical; each R can be the same or different; wherein each R<sup>1</sup> can be H or any organic or inorganic radical, each R<sup>1</sup> can be the same or different;  $x \geq 1$ ; preferable  $x \geq 2$  and y has a value from 0 to 1. Examples of organic radicals are alkyl or aryl radicals. Examples of inorganic radicals are Si and Ge. This list is exemplary only and not limiting. The most preferred embodiment is emeraldine base form of the polyaniline wherein y has a value of approximately 0.5. The base form is the non-doped form of the polymer. The non-doped form of polyaniline and the non-doped form of the other conducting polymers is herein referred to as the electrically conducting polymer precursor.

In Fig. 2, polyaniline is shown doped with a dopant. In this form, the polymer is in the conducting form. If the polyaniline base is exposed to cationic species QA, the nitrogen atoms of the imine (electron rich) part of the polymer becomes substituted with the Q<sup>+</sup> cation to form an emeraldine salt as shown in Fig. 2. Q<sup>+</sup> can be selected from H<sup>+</sup> and organic or inorganic cations, for example, an alkyl group or a metal.

QA can be a protic acid where Q is hydrogen. When a protic acid, HA, is used to dope the polyaniline, the nitrogen atoms of the imine part of the polyaniline are protonated. The emeraldine base form is greatly stabilized by resonance effects. The charges distribute through the nitrogen atoms and aromatic rings making the imine and amine nitrogens indistinguishable. The actual structure of the doped form is a delocalized polysemiquinone radical cation as shown in Fig. 3.

The emeraldine base form of polyaniline is soluble in various organic solvents and in various aqueous acid solutions. Examples of organic solvents are dimethylsulfoxide (DMSO), dimethylformamide (DMF) and N-methylpyrrolidinone (NMP), dimethylene propylene urea, tetramethyl urea, etc. This list is exemplary only and not limiting. Examples of aqueous acid solutions is 80% acetic acid and 60-88% formic acid. This list is exemplary only and not limiting.

Polyaniline base is generally processed by dissolving the polymer in NMP. These solutions exhibit a bimodal or trimodal distribution in Gel Permeation Chromatography (GPC) as a result of aggregation induced by internal hydrogen bonding between chains as previously described in U.S. patent application serial no. 08/370,128, filed on January 9, 1995, the teaching of which is incorporated herein by reference. The GPC curve for typical polyaniline base in NMP is shown in Figure 4.

Polymers in general can be amorphous, crystalline, or partly crystalline. In the latter case, the polymer consists of crystalline phases and amorphous phases. The morphology of a polymer is very important in determining the polymer's physical, mechanical, and electronic properties.

Polyaniline base films processed from NMP either by spin-coating or by solution casting techniques are amorphous as can be seen in Figure 5a which depicts the Wide Angle X-Ray Scattering (WAXS) spectrum for this material. Amorphous diffuse scattering is observed. Some crystallinity is induced in these films by post processing mechanical deformation especially if these films are derived from gels as described by A.G. MacDiarmid et al in Synth. Met. 55-57, 753 (1993). WAXS of a stretch oriented film having been stretched ( $l/l_0 = 3.7X$ ) derived from a gel is shown in Figure 5b. Some

crystallinity has been induced as compared to the non-stretch oriented films as evidenced by the defined scattering peaks.

Doping the amorphous polyaniline base films (those having structure shown in Figure 5a) with aqueous hydrochloric acid results in isotropic conductivity of 1 S/cm. Such films are not crystalline. Similar doping of stretch oriented films results in anisotropic conductivity where conductivity on the order of  $10^2$  S/cm is measured parallel to the stretch direction whereas conductivity on the order of  $10^0$  S/cm is measured perpendicular to the stretch direction. It should also be noted that some level of crystallinity is lost during the doping process in these films.

According to the present invention, the interchain (polymer chain) registration is increased as compared to a stretch oriented film.

Figures 7 and 8 show the dynamic mechanical thermal analysis (DMTA) spectrum for a polyaniline base film processed from NMP alone. Figure 7 is the first scan where a  $T_g$  of approx. 118 is observed as a result of the residual NMP which is present in the film. Figure 8 is the second thermal scan of the same film. This film has no residual solvent and a  $T_g$  of  $\approx 251$  °C is measured for the polyaniline base polymer.

When an additive such as a plasticizer, such as a poly-co-dimethyl propylamine siloxane, is added to the polyaniline base completely different properties and morphology is observed. The siloxane has a polar amine group which facilitates the miscibility of the polyaniline base and the plasticizer. The DMTA of a polyaniline base film cast from NMP and containing 5% by weight to polyaniline of the poly-co-dimethyl propyl amine siloxane exhibits a lower  $T_g$  on the first thermal scan as compared to polyaniline base

processed from NMP alone (Figure 9) as a result of plasticization induced by the siloxane. However, on the second thermal scan of this film (Figure 10), the polymer exhibits an increase in T<sub>g</sub> as compared to polyaniline processed from NMP. When the polysiloxane is added to a solution of polyaniline base, the siloxane due to the polar amine group can interact with the polymer chains and disrupt some of the polyaniline interactions with itself or some of the aggregation. Thus, the polysiloxane first induces some deaggregation. However, the polysiloxane has multiple amine sites and thus, it can itself hydrogen bond with multiple polyaniline base chains and thus, the polysiloxane facilitates the formation of a cross-linked network. This cross-linked network accounts for the increased T<sub>g</sub> observed in the DMTA. T<sub>g</sub> is characteristic of the amorphous regions of a polymer and in this case the amorphous regions consist of a cross-linked polyaniline/polysiloxane network. Thus, the polysiloxane is inducing an antiplasticization effect in polyaniline base as the T<sub>g</sub> is increased. Generally, plasticizers reduce T<sub>g</sub>. GPC data (Figure 11) is consistent with this model. The addition of the poly-amino containing siloxane to a polyaniline base solution in NMP results in a significant increase in the high molecular weight fractions depicting the cross-linked network which forms between polyaniline and the plasticizer.

In addition to the cross-linked network the siloxane induces in the amorphous regions, concomitantly it also is found to induce significant levels of crystallinity in polyaniline base as a result of the local mobility that it provides. Figure 5c shows the WAXS for a polyaniline base film processed from NMP containing 10% of the poly amino containing siloxane. As can be seen highly crystalline polyaniline has been attained. Much higher levels of crystallinity as compared to figure 5b for the stretch oriented films.

Thus polyaniline by the addition of the siloxane forms a structure depicted in Figure 6 where crystalline regions of highly associated polyaniline chains (outlined by a rectangle) are formed with interstitial amorphous regions. In most cases, the additive resides in the amorphous interstitial sites. The degree of crystallinity (number of crystalline sites) and the size of the crystalline domains as well as the degree of amorphous regions and the nature of the amorphous region (aggregated, i.e. cross-linked or not) can be tuned by the type and amount of additive. In turn, by controlling the above, the properties of the material can also be controlled.

With the poly-co-dimethyl aminopropyl siloxane (5% N content), loadings ranging from .001 to 20 % by weight gives highly crystalline polyaniline. The highly crystalline polyaniline in turn exhibits increased modulus, stiffness, yield and tensile strengths, hardness, density and softening points. Thus, the siloxane at these loadings is having an antiplasticization effect. Above 20% loading, the crystallinity begins to decrease. As the crystallinity decreases, the modulus, stiffness, yield and tensile strengths, hardness, density and softening points begin to decrease. Thus, the siloxane at these loadings begins to have a plasticization effect. The siloxane content becomes high enough that it disrupts the polyaniline base interactions in the crystalline regions. With the poly co-dimethyl aminopropyl siloxanes having .5 and 13% N ratios, similar trends are observed but the particular amount of siloxane needed to have a plasticization effect or an antiplasticization effect varies. Thus, the degree of crystallinity and the degree of amorphous regions and in turn the properties of polyaniline can be tuned by the nature of the additive as well as the amount of additive. Indeed, using the same additive but simply changing the loading dramatically changes the morphology and in turn the properties of polyaniline.

The electronic properties of the polymer are also impacted. The conductivity of a polyaniline base film cast from NMP and containing 1% by weight poly-co-dimethyl aminopropyl siloxane which is doped by aqueous hydrochloric acid is 50 S/cm as compared to 1 S/cm for a polyaniline film with no plasticizer. This is isotropic conductivity. The doped film containing the polysiloxane retains the highly crystalline structure.

The degree of crystallinity and the degree of amorphous regions and in turn the physical, mechanical, and electronic properties can be tuned by the particular additive used and by the amount of additive. For example, the Tg of polyaniline can be increased or decreased by the amount and type of additive. The mechanical properties such as tensile properties, modulus, impact resistance, etc. can be tuned as described above. The additive can range from .001 to 90% by weight, more preferably from .001 to 50% and most preferably from .001 to 25%. A list of plasticizers that can be used to practice the present invention is given in Table 1. The plasticizer can be small molecules, oligomeric or polymeric in nature as can be seen in Table 1. They can be monofunctional, bifunctional, and multifunctional. The additive can also be removed from the final film structure if so desired by appropriate extraction.

### Specific Examples

**Polyaniline Synthesis** Polyaniline is synthesized by the oxidative polymerization of aniline using ammonium peroxydisulfate in aqueous hydrochloric acid. The polyaniline hydrochloride precipitates from solution. The polymer is then neutralized using aqueous ammonium hydroxide. The neutralized or non-dope polyaniline base is then filtered, washed and dried. Polyaniline can also be made by electrochemical oxidative

polymerization as taught by W. Huang, B. Humphrey, and A.G. MacDiarmid, J. Chem. Soc., Faraday Trans. 1, 82, 2385, 1986.

**Polyaniline Base in NMP:** The polyaniline base powder is readily dissolved in NMP up to 5% solids. Thin films (on the order of a micron) can be formed by spin-coating. Thick films are made by solution casting and drying (70 ° C in vacuum oven under a nitrogen purge for 15 hours). These solutions and films have the properties described above.

#### **Polyaniline Base in NMP/Plasticizer**

a. Polyaniline Base was first dissolved in NMP to 5% solids and allowed to mix well. A poly-co-dimethyl, aminopropyl siloxane (N content 5% relative to repeat unit) was dissolved to 5% in NMP. The siloxane solution was added to the polyaniline base solution. The resulting admixture was allowed to mix for 12 hours at room temperature. A number of solutions were made having from .001 % to 50% siloxane content (by weight relative to polyaniline). Thin films were spin-coated onto quartz substrates; Thick films were prepared by solution casting and baking the solutions at 70 ° C in a vacuum oven under a Nitrogen purge for 15 hours). The solutions and the films have the properties described above.

b. The same experiment described in (a) was carried out except that the plasticizer was a poly-co-dimethyl, aminopropyl siloxane in which the N content was 13%.

c. The same experiment described in (a) was carried out except that the plasticizer was a poly-co-dimethyl, aminopropyl siloxane in which the N content was .5%.

d. The same experiment described in (a) was carried out except that the plasticizer was polyglycol diacid.

e. The same experiment described in (a) was carried out except that the plasticizer was 3,6,9-trioxaundecanedioic acid.

f. The same experiment described in (a) was carried out except that the plasticizer was poly(ethylene glycol) tetrahydro furfuryl ether.

g. The same experiment described in (a) was carried out except that the plasticizer was glycerol triacetate.

h. The same experiment described on (a) was carried out except the plasticizer was epoxidized soy bean oil.

#### **Polyaniline Base in NMP/m-Cresol/Plasticizer**

The same experiment as described in (a) was carried out except that polyaniline base and the plasticizer was dissolved in NMP/m-Cresol mixtures in which m-Cresol ranged from 1 to 99%

#### **Polyaniline Base in m-Cresol/Plasticizer**

The same experiment as described in (a) was carried out except that the polyaniline base was dissolved in m-Cresol and the plasticizer was dissolved in m-Cresol.

#### **Polyaniline Base in m-Cresol and in NMP/m-Cresol**

Polyaniline Base was dissolved in m-Cresol and in NMP/m-Cresol combinations to 5% solids. The m-Cresol in the latter system being the additive ranged from 1 to 99%.

Free-Standing films were made by solution casting techniques. With increasing m-cresol content, the polyaniline exhibited a WAXS similar to that shown in Figure 5a except that the amorphous scattering peak became somewhat sharper indicative of some crystallinity. However, this was significantly less than observed with the siloxane plasticizer.

## Doped Polyanilines

### 1. Hydrochloric Acid and/or Methanesulfonic Acid Doped Films

Polyaniline base films made as described above were doped by aqueous acid solutions of hydrochloric or methanesulfonic acid. The films were immersed in the acid solution for 12 hours for thin films and 36 hours for the thick films. The conductivity of a polyaniline base film processed from NMP and doped with these acid solutions is 1 S/cm. The conductivity of a base film processed from NMP and 1 % poly-co- dimethyl, aminopropyl siloxane (5%N content) was 50 S/cm.

### 2. Sulfonic Acid Doped Polyanilines

Polyaniline Base was dissolved in a solvent such as NMP or NMP/m-Cresol combinations, etc. from 1 to 5% solids. To this solution was added a dopant such as camphorsulfonic acid or acrylamidopropanesulfonic acid (previously reported in U.S. Patent Application Serial No. 595,853 filed on February 2, 1996). These solutions were used to spin-coat or solution cast films. In some experiments, the plasticizer such as the poly-co-dimethyl,aminopropyl siloxane in a solvent was added to the doped polyaniline solution. In certain other experiments, the plasticizer was first added to the pani base

solution. The dopant was then added to the polyaniline solution containing the plasticizer.

The teaching of the following U.S. Patent Applications are incorporated herein by reference:

"CROSS-LINKED ELECTRICALLY CONDUCTIVE POLYMERS, PRECURSORS THEREOF AND APPLICATIONS THEREOF", Application Serial No. 595,853, filed February 2, 1996;

"METHODS OF FABRICATION OF CROSS-LINKED ELECTRICALLY CONDUCTIVE POLYMERS AND PRECURSORS THEREOF", Application Serial No. 594,680, filed February 2, 1996;

"DEAGGREGATED ELECTRICALLY CONDUCTIVE POLYMERS AND PRECURSORS THEREOF", Application Serial No. 370,127, filed January 9, 1995; and

"METHODS OF FABRICATION OF DEAGGREGATED ELECTRICALLY CONDUCTIVE POLYMERS AND PRECURSORS THEREOF", Application Serial No. 370,128, filed January 9, 1995.

While the present invention has been shown and described with respect to a preferred embodiment, it will be understood that numerous changes, modifications, and improvements will occur to those skilled in the art without departing from the spirit and scope of the invention.

TABLE I

## PLASTICIZERS

## ADIPIC ACID DERIVATIVES

Dicapryl adipate  
Di-(2-ethylhexyl) adipate  
Di-(n-heptyl, n-nonyl) adipate  
Diisobutyl adipate  
Diisodecyl adipate  
Dinonyl adipate  
Di-(tridecyl) adipate

## AZELAIC ACID DERIVATIVES

Di-(2-ethylhexyl) azelate  
Diisodecyl azelate  
Diisooctyl azelate  
Dimethyl azelate  
Di-n-hexyl azelate

## ISOPHTHALIC ACID DERIVATIVES

Diethylene glycol dibenzoate  
Dipropylene glycol dibenzoate  
Polyethylene glycol 200 dibenzoate

## TRIMELLITIC ACID DERIVATIVES

Acetyl tri-n-butyl citrate  
Acetyl triethyl citrate  
Tri-n-butyl citrate  
Triethyl citrate

## TETRAHYDROPHthalIC ACID DERIVATIVES

Bis-(2-hydroxyethyl) dimerate

## EPOXY DERIVATIVES

Epoxidized linseed oil  
Epoxidized soybean oil  
2-Ethylhexyl epoxystallate  
n-Octyl epoxystereate

## FUMARIC ACID DERIVATIVES

Dibutyl fumarate

## GLYCEROL DERIVATIVES

Glycerol triacetate

## BUTYRIC ACID DERIVATIVES

2,4-Trimethyl-1,3-pentanediol  
Diisobutyrate

## ISOPHTHALIC ACID DERIVATIVES

Di-(2-ethylhexyl) isophthalate  
Dimethyl isophthalate  
Diphenyl isophthalate

## LAURIC ACID DERIVATIVES

Methyl laurate

## LINOLEIC ACID DERIVATIVE

Methyl linoleate, 75%

## MALEIC ACID DERIVATIVES

Di-(2-ethylhexyl) maleate  
Di-n-butyl maleate

## MELLITATES

Tricapryl trimellitate  
Tri-(2-ethylhexyl) trimellitate  
Trisodecyl trimellitate  
Tri-(n-octyl, n-decyl) trimellitate

## MYRISTIC ACID DERIVATIVES

Isopropyl myristate

## OLEIC ACID DERIVATIVES

Butyl oleate  
Glycerol monooleate  
Glycerol trioleate  
Methyl oleate  
n-Propyl oleate  
Tetrahydrofurfuryl oleate

## PALMITIC ACID DERIVATIVES

Isopropyl palmitate  
Methyl palmitate

## PARAFFIN DERIVATIVES

Chloroparaffin, 41% C1  
Chloroparaffin, 50% C1  
Chloroparaffin, 60% C1  
Chloroparaffin, 70% C1

## PHOSPHORIC ACID DERIVATIVES

2-Ethylhexyl diphenyl phosphate  
Isodecyl diphenyl phosphate  
t-Butylphenyl diphenyl phosphate  
Tri-butoxyethyl phosphate  
Tributyl phosphate  
Tri-cresyl phosphate  
Triphenyl phosphate

## PHthalIC ACID DERIVATIVES

Butyl benzyl phthalate  
Butyl octyl phthalate  
Dicapryl phthalate  
Dicyclohexyl phthalate  
Di-(2-ethylhexyl) phthalate  
Diethyl phthalate  
Dihexyl phthalate  
Diisobutyl phthalate  
Diisodecyl phthalate  
Diisononyl phthalate  
Diisooctyl phthalate  
Dimethyl phthalate  
Ditridecyl phthalate  
Diundecyl phthalate

## RICINOLEIC ACID DERIVATIVES

Butyl ricinoleate  
Glyceryl tri(acetyl) ricinoleate  
Methyl acetyl ricinoleate  
Methyl ricinoleate  
n-Butyl acetyl ricinoleate  
Propylene glycol ricinoleate

## SEBACIC ACID DERIVATIVES

Dibutyl sebacate  
Di-(2-ethylhexyl) sebacate  
Dimethyl sebacate

## STEARIC ACID DERIVATIVES

Ethylene glycol monostearate  
Glycerol monostearate  
Isopropyl isostearate  
Methyl stearate  
n-Butyl stearate  
Propylene glycol monostearate

## SUCCINIC ACID DERIVATIVES

Diethyl succinate

## SULFONIC ACID DERIVATIVES

N-Ethyl o,p-toluenesulfonamide  
o,p-toluenesulfonamide

### *Polyesters*

adipic acid polyester  
Paraplex G-40  
adipic acid polyester  
Santicizer 334F  
azelaic acid polyester  
Plastolein 9720)  
azelaic acid polyester  
Plastolein 9750  
sebacic acid polyester  
Paraplex G-25

### *Sucrose derivatives*

sucrose acetate-isobutyrate (SAIB)

### *Tartaric acid derivative*

dibutyl tartrate

### *Terephthalic acid derivative*

bis(2-ethylhexyl) terephthalate  
(DOTP)

### *Trimellitic acid derivatives*

tris(2-ethylhexyl) trimellitate  
(TOTM)

heptyl nonyl trimellitate

heptyl nonyl undecyl trimellitate

triisodecyl trimellitate

### *Glycol derivatives*

diethylene glycol dipelargonate

triethylene glycol di 2

ethylbutyrate

poly(ethylene glycol) (200) di 2

ethylhexanoate

### *Glycolates*

methyl phthalyl ethyl glycolate

butyl phthalyl butyl glycolate

### *Hydrocarbons*

hydrogenated terphenyls HB-40

poly(alkyl naphthalene)s Panaflex

aliphatic aromatics Leromoll

chlorinated paraffin (52 wt % Cl),

Cereclor S-52

## Terpenes and Derivatives

Camphor

Hydrogenated methyl ester or rosin

## Phosphonic Acid Derivatives

Chlorinated Polyphosphanate

## Siloxanes

Polydimethyl siloxane

Polyco-dimethyl/propylamine siloxanes with various amount of propylamine content

Polydiphenylsiloxanes

Polyco-dimethylphenyl siloxanes

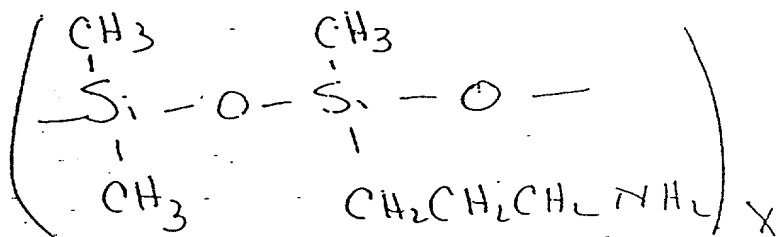
Silanol terminated polysiloxanes

Amino terminated polysiloxanes

Epoxy terminated polysiloxanes

Carbirol terminated polysiloxanes

Polysilanes



## Glycols

Polyethylene glycol

Poly(ethylene glycol) tetrahydrofurfuryl ether

Poly(ethylene glycol) bis (carboxymethyl) ether

3.6.9 - trioxadecanoic acid

3.6.9 - trioxaundecanedioic acid

Polyglycol diacid